

# FeynHiggs2.1: A High Precision Tool for Higgs Physics at the LHC

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based on collaboration with  
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1. Motivation
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3. The code *FeynHiggs2.1*
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# 1. Motivation

One of the main tasks of the LHC:

- ⇒ find the Higgs boson
- ⇒ determine its properties
- ⇒ explore the underlying model

Simplest solution: Higgs in the Standard Model (SM)

Attractive solution:

Higgs in the Minimal Supersymmetric Standard Model (MSSM)

LHC measurements ↔ theory predictions

Necessary: predictions of masses, couplings, BR's, ...

... in a variety of models:

real MSSM , complex MSSM , non-minimal flavor violation MSSM , ...  
(and also in the SM)

... to be able to handle all possibilities

general case: complex MSSM (real MSSM as special case)

Higgs potential of the cMSSM contains two Higgs doublets:

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$
$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

Five physical states:  $h^0, H^0, A^0, H^\pm$  (no CPV at tree-level)

Input parameters:  $\tan \beta = \frac{v_2}{v_1}$ ,  $M_A$  or  $M_{H^\pm}$

Contrary to the SM:  $m_h$  is not a free parameter

MSSM tree-level bound:  $m_h < M_Z$ , excluded by LEP Higgs searches

Large radiative corrections:

Dominant one-loop corrections:  $\sim G_\mu m_t^4 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

Upper bound on  $m_h$  in the MSSM:

“Unconstrained (real) MSSM”:

$M_A$ ,  $\tan\beta$ , 5 parameters in  $\tilde{t}$ - $\tilde{b}$  sector,  $\mu$ ,  $m_{\tilde{g}}$ ,  $M_2$

*FeynHiggs*  $\Rightarrow m_h \lesssim 135$  GeV

[S. H., W. Hollik, G. Weiglein '99] ,

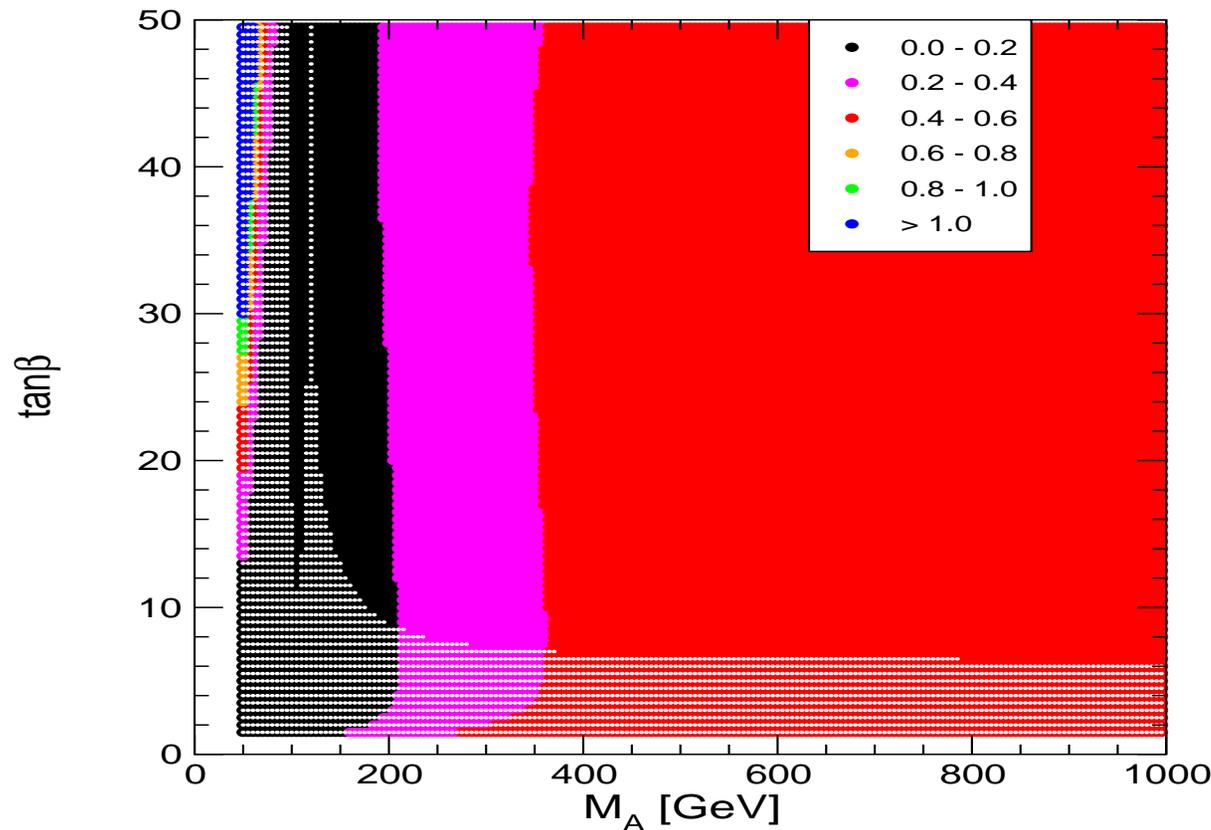
[G. Degrandi, S. H., W. Hollik, P. Slavich, G. Weiglein '02]

for  $m_t = 175$  GeV, no theoretical uncertainties included  
(holds also for the complex case)

Dominant one-loop corrections:  $\sim G_\mu m_t^4 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Measurement of  $m_h$ , Higgs couplings  $\Rightarrow$  test of the theory



LHC:  $\Delta m_h \approx 0.2$  GeV  
 $\Rightarrow m_h$  will be precision observable

... if  $gg \rightarrow h \rightarrow \gamma\gamma$  is not suppressed

Possible in the MSSM:

gluophobic Higgs scen.

[M. Carena, S.H., C. Wagner,

G. Weiglein '02]

strong suppression over whole  $M_A$ - $\tan\beta$  plane

## 2. Higgs physics in the (c)MSSM

### Status of $m_h$ prediction in the rMSSM:

- Complete one-loop result
- + all presumably dominant two-loop corrections known for real MSSM

Used for final LEP analyses: *FeynHiggs1.3*

[S.H., W. Hollik, G. Weiglein '98, '00, '02]

### Remaining theoretical uncertainties in prediction for $m_h$ :

[G. Degrossi, S. H., W. Hollik, P. Slavich, G. Weiglein'02] ,

[M. Frank, S. H., W. Hollik, G. .W. '02]

- From unknown higher-order corrections:

$$\Rightarrow \Delta m_h \approx 3 \text{ GeV}$$

- From uncertainties in input parameters:

$$m_t, \dots, M_A, \tan \beta, m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{g}}, \dots$$

$$\Delta m_t \approx 5 \text{ GeV} \Rightarrow \Delta m_h \approx 5 \text{ GeV}$$

## Status of calculations in the cMSSM and uncertainties:

### Known:

- fermion/sfermion corrections at 1-loop,  $q^2 = 0$
- some leading logs from remaining sectors
- leading 2-loop corrections

[A. Pilaftsis '98] , [A. Pilaftsis, C. Wagner '99] , [A. Demir '99] , [S. H. '01]

[S. Choi, M. Drees, J. Lee '00] , [M. Carena, J. Ellis, A. Pilaftsis, C. Wagner '00, '01]

[T. Ibrahim, P. Nath '01, '02] , [S. Ham, C. Kim, S. Oh, D. Son, E. Yoo '02]

### Unknown:

- remaining sectors at 1-loop (rMSSM: 5 GeV )
- $q^2$  dependence at 1-loop (rMSSM:  $\sim 2$  GeV )

[M. Frank, S. H., W. Hollik, G. Weiglein '02]

⇒ Uncertainties much larger than in the rMSSM

## Effects of complex parameters in the Higgs sector:

Complex parameters enter via loop corrections:

- $\mu$  : Higgsino mass parameter
- $A_{t,b,\tau}$  : trilinear couplings  $\Rightarrow X_{t,b,\tau} = A_{t,b} - \mu^* \{\cot \beta, \tan \beta\}$  complex
- $M_{1,2}$  : gaugino mass parameter (one phase can be eliminated)
- $m_{\tilde{g}}$  : gluino mass

$\Rightarrow$  can induce  $\mathcal{CP}$ -violating effects

Result:

$$(A, H, h) \rightarrow (h_3, h_2, h_1)$$

with

$$m_{h_3} > m_{h_2} > m_{h_1}$$

## Inclusion of higher-order corrections:

(→ Feynman-diagrammatic approach)

Propagator / mass matrix with higher-order corrections:

$$\begin{pmatrix} q^2 - M_A^2 + \hat{\Sigma}_{AA}(q^2) & \hat{\Sigma}_{AH}(q^2) & \hat{\Sigma}_{Ah}(q^2) \\ \hat{\Sigma}_{HA}(q^2) & q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hA}(q^2) & \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$  ( $i, j = h, H, A$ ) : renormalized Higgs self-energies

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0 \Rightarrow \mathcal{CPV}$ ,  $\mathcal{CP}$ -even and  $\mathcal{CP}$ -odd fields can mix

Our result for  $\hat{\Sigma}_{ij}$ :

- full 1-loop evaluation: dependence on all possible phases included
- most up-to-date 2-loop corrections in rMSSM (complex phases neglected at two-loop level)
- momentum dependence fully included at 1-loop
- on-shell renormalization scheme

Result:  $(A, H, h) \rightarrow (h_3, h_2, h_1)$  with  $m_{h_3} > m_{h_2} > m_{h_1}$

Higgs boson couplings:

(in  $q^2 = 0$  approximation)

$$\begin{pmatrix} h_3 \\ h_2 \\ h_1 \end{pmatrix} = \begin{pmatrix} u_{11} & u_{12} & u_{13} \\ u_{21} & u_{22} & u_{23} \\ u_{31} & u_{32} & u_{33} \end{pmatrix} \cdot \begin{pmatrix} A \\ H \\ h \end{pmatrix}$$

- $h_1, h_2, h_3$  : neutral Higgs boson with  $CPV$  couplings
- $u_{12}, u_{13}, u_{21}, u_{31}$  :  $CPV$  mixings
- $u_{ij}$  determine Higgs-fermion and Higgs-gauge boson couplings

### 3. The code FeynHiggs2.1

[M. Frank, T. Hahn, S. H., W. Hollik, G. Weiglein '03]

Latest version: (03/04)

contains all above described results

- evaluation of the Higgs sector of the (c)MSSM:
  - full 1-loop,  $q^2 \neq 0$
  - leading/subleading 2-loop
- full 1-loop corrections for charged Higgs sector

Further features:

- New renormalization ( $\overline{\text{MS}}/\text{OS}$ ) for 1-loop result  
[M. Frank, S. H., W. Hollik, G. Weiglein '02]
- “ $\Delta m_b$ ” corrections for Higgs masses, couplings, etc.  
⇒ leading  $\mathcal{O}(\alpha_b \alpha_s)$  terms included  
[M. Carena, D. Garcia, U. Nierste, C. Wagner '00]
- most recent: subleading  $\mathcal{O}(\alpha_t \alpha_b, \alpha_b^2)$  terms (currently implemented )  
[A. Dedes, G. Degrassi, P. Slavich '03]

Included in *FeynHiggs2.1* (I):

Evaluation of all Higgs boson masses and mixing angles (cMSSM/rMSSM)

- $m_{h_1}, m_{h_2}, m_{h_3}, M_{H^\pm}, \alpha_{\text{eff}}, u_{ij}, \dots$

Evaluation of all neutral Higgs boson decay channels (cMSSM/rMSSM)

- total decay width  $\Gamma_{\text{tot}}$
- $\text{BR}(h_i \rightarrow f\bar{f})$ : decay to SM fermions
- $\text{BR}(h_i \rightarrow \gamma\gamma, ZZ, WW, gg)$ : decay to SM gauge bosons
- $\text{BR}(h_i \rightarrow h_1 Z, h_1 h_1)$ : decay to gauge and Higgs bosons
- $\text{BR}(h_i \rightarrow \tilde{f}_i \tilde{f}_j)$ : decay to sfermions
- $\text{BR}(h_i \rightarrow \tilde{\chi}_i^\pm \tilde{\chi}_j^\pm, \tilde{\chi}_i^0 \tilde{\chi}_j^0)$ : decay to charginos, neutralinos

Evaluation for the SM Higgs (same masses as the three MSSM Higgses)

- total decay width  $\Gamma_{\text{tot}}^{\text{SM}}$
- $\text{BR}(h_i^{\text{SM}} \rightarrow f\bar{f})$ : decay to SM fermions
- $\text{BR}(h_i^{\text{SM}} \rightarrow \gamma\gamma, ZZ, WW, gg)$ : decay to SM gauge bosons

Included in *FeynHiggs2.1* (II):

Evaluation of all charged Higgs boson decay channels (cMSSM/rMSSM)

- total decay width  $\Gamma_{\text{tot}}$
- $\text{BR}(H^+ \rightarrow f\bar{f}')$ : decay to SM fermions
- $\text{BR}(H^+ \rightarrow h_i W^+)$ : decay to gauge and Higgs bosons
- $\text{BR}(H^+ \rightarrow \tilde{f}_i \tilde{f}'_j)$ : decay to sfermions
- $\text{BR}(H^+ \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^+)$ : decay to charginos and neutralinos

Evaluation of additional couplings:

- $g(V \rightarrow Vh_i, h_i h_j)$ : coupling of gauge and Higgs bosons
- $g(h_i h_j h_k)$ : all Higgs self couplings (including charged Higgs)
- $\sigma(\gamma\gamma \rightarrow h_i)$ : Higgs production XS at a  $\gamma C$

Included in *FeynHiggs2.1* (III):

Evaluation of masses, mixing and decay in the NMFV MSSM

NMFV: Non Minimal Flavor Violation

⇒ Connection to Flavor physics

[*S.H., W. Hollik, F. Merz, S. Peñaranda '04*]

Evaluation of additional constraints (cMSSM/rMSSM)

- $\rho$ -parameter:  $\Delta\rho$  at  $\mathcal{O}(\alpha)$ ,  $\mathcal{O}(\alpha\alpha_s)$ , ...  
 $\Delta\rho \gtrsim 2 \times 10^{-3}$  indicates experimentally disfavored  $\tilde{t}/\tilde{b}$  masses
- anomalous magnetic moment of the  $\mu$ :  $(g_\mu - 2)_{\text{SUSY}}$   
evaluation of full one-loop and leading/subleading two-loop SUSY corrections [*S.H., D. Stöckinger, G. Weiglein '03*]

Planned:

- $\text{BR}(b \rightarrow s\gamma)$  and similar observables

## How does it work?

1. Go to [www.feynhiggs.de](http://www.feynhiggs.de)
2. Download the latest version (possibly also *LoopTools*)
3. type `./configure, make`  
⇒ library `libFH.a` is created
4. 3 possible ways to use *FeynHiggs*:
  - A) as a stand alone program
  - B) called from a Fortran/C++ code
  - C) called within Mathematicaprocessing of [Les Houches Accord data](#) possible
5. Detailed [instructions](#) and [help](#) are provided in the [man pages](#)

Example of application: *FeynHiggs* is used for

- final evaluations of [LEP Higgs WG](#) for *CPV* scenario (together with CPH)  
[*P. Bechtle, K. Desch, priv. comm.*]
- [ATLAS Higgs](#) analyses [*M. Schumacher, priv. comm.*]

## A) Stand alone program

- Prepare **input file**:

```
MSusy          500
MHp            1000
TB             3 [ 50 20 1]
absAt          800
argAt          0.5
...
```

[ 50 20 1] one- or two-dim. loops possible (here with 20 log steps)

- call *FeynHiggs*:

```
./FeynHiggs var.in 4003023110 [| table TB > out.dat]
```

**var.in** : input file (any name possible)

**4003023110** : options (precision, r/cMSSM, ... )

- output to screen (human readable)

output to file (machine readable) via [| table TB > out.dat]

## Possible screen output:

```
...
# MSusy      = 500.0000      input parameter
# MSQ        = 500.0000
# MSU        = 500.0000
...
# MStop      = 441.2194  601.6737      derived parameters
...
# mssmpart = 4      options
# tanbren = 0
...
115.3965411987924      # Mh1      Higgs masses
996.5635802372443      # Mh2
996.8233893296986      # Mh3
1000.0000000000000      # MHp
...
0.9999997      0.3374385E-05      0.7663596E-03      # UHiggs 123=(U)hHA      mixing matrix
0.7663236E-03      0.1514869E-03      -0.9999997
-0.3490518E-05      1.0000000      0.1514842E-03
...
```

## Possible screen output (cont.):

```
...
# h1 decays
# Gamma          BR          BR(SM)           $\Gamma_h$ , BRs
#-----
0.2075287E-02    0.7504491    0.7505097      # h1/h -> bb
...
0.1572622E-03    0.5686793E-01  0.5945727E-01  # h1/h -> WW(*)
...
0.0000000E+00    0.0000000E+00  0.0000000E+00  # h1/h -> Stop1+ Stop1-
...
#
# h2 decays
# Gamma          BR          BR(SM)
#-----
0.5584675        0.5889041E-01  0.9500386E-01  # h2/H -> tt
...
# constraints:          constraints
#
2.1096020875051806E-004 # delta_rho_SUSY
7.2377882430306384E-010 # g-2_SUSY
...
```

## B) Called from a Fortran/C++ code

Link *FeynHiggs* as a subroutine

`call FHSetFlags( ... ) :`

→ specification of accuracy etc.

`call FHSetPara( ... ) :`

→ specify input parameters

`call FHGetPara( ... ) :`

→ obtain derived parameters

`call FHHiggsCorr( ... ) :`

→ obtain Higgs boson masses and mixings

`call FHCouplings( ... ) :`

→ obtain decay widths, BRs etc.

## C) Called within Mathematica

- install the **math link** to *MFeynHiggs* , e.g.:

```
Install[,'MFeynHiggs']
```

- **FHSetFlags[ ... ]** :  
→ specification of accuracy etc.

```
FHSetPara[ ... ] :
```

→ specify input parameters

```
FHGetPara[] :
```

→ obtain derived parameters

```
FHHiggsCorr[] :
```

→ obtain Higgs boson masses and mixings

```
FHCouplings[] :
```

→ obtain decay widths, BRs etc.

## Processing Les Houches Accord data (LHA: [*P. Skands et al. '03*] )

- call *FeynHiggs* with input file (from spectrum generator, ... )

`FeynHiggs LHA/Isajet.spc 4002023111`

`LHA/Isajet.spc` : input file (needs 'LHA' in the name/path)

`4002023111` : options (as before)

- *FeynHiggs* reads all necessary data
- *FeynHiggs* evaluates the Higgs boson masses, couplings, BRs, etc.
- `FeynHiggs.spc.dec` is created

all input data remains

Higgs masses and mixing angles are overwritten

Higgs BRs etc. are added

- Alternatively: within a Fortran code:

```
call LHA_in( ... ) , call LHA_out( ... )
```

## 4. Comparison with other calculations

Other calculations/codes:

- Hdecay3.0 (pure real case) [*M. Spira et al.*]
- CPsH (real and complex MSSM) [*J. Lee, A. Pilaftsis et al. '03*]  
(rMSSM: CPsH and Hdecay3.0(default) should agree)

### Comparison in the rMSSM:

masses, mixings, ... : more included in *FeynHiggs2.1*  
⇒ compare with CPsH/Hdecay3.0

### Comparison in the cMSSM:

analysis more involved:

some corrections included in *FeynHiggs*, but not in CPsH (one-loop)

some corrections included in CPsH, but not in *FeynHiggs* (two-loop)

⇒ not completely clear what causes differences

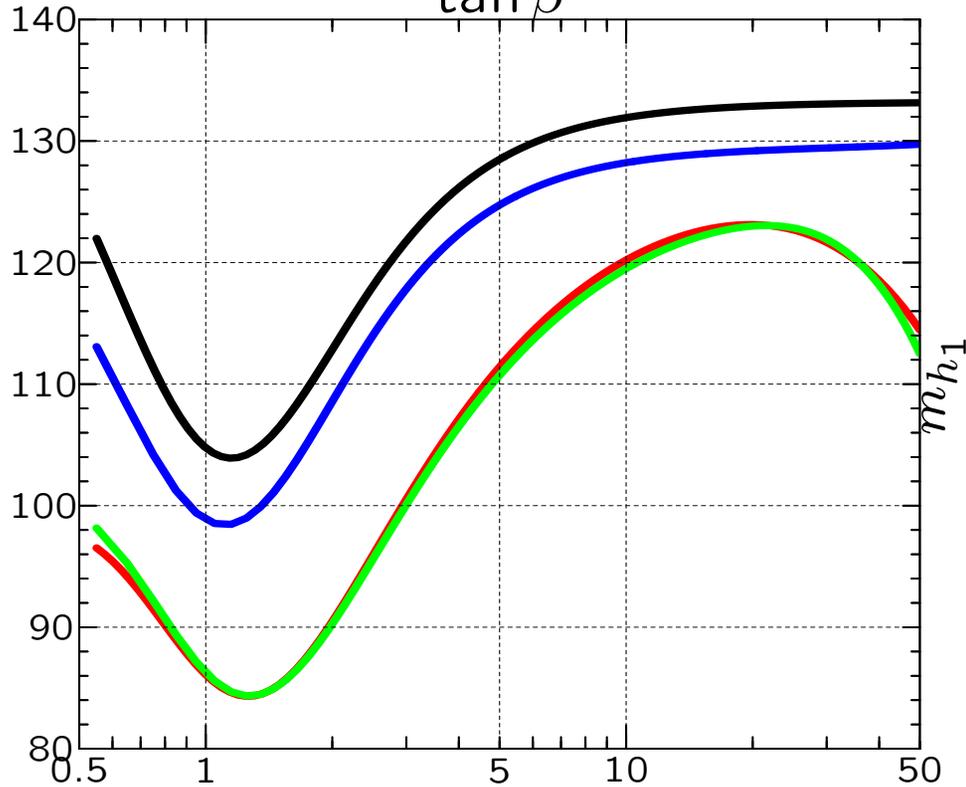
(but differences from real MSSM also present here)

→ qual. /quant. agreement for BRs with CPsH

Compare  $m_{h_1}$  in the two scenarios:

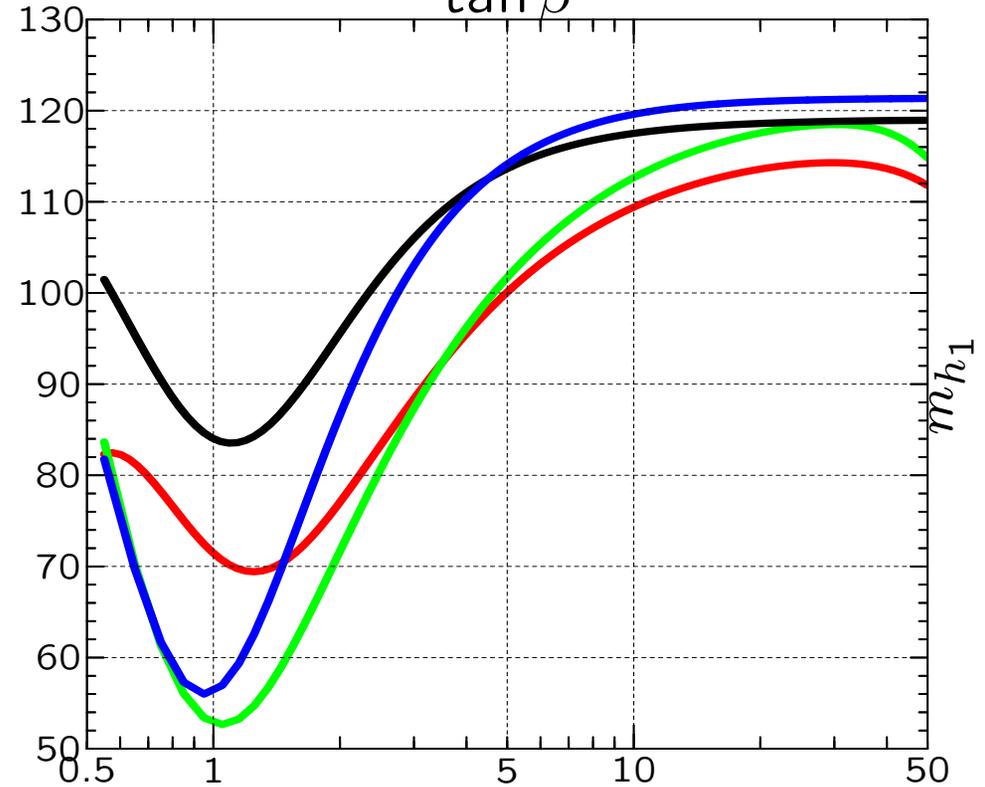
$m_h^{\max}$  scenario

$\tan \beta$



gluophobic Higgs scenario

$\tan \beta$

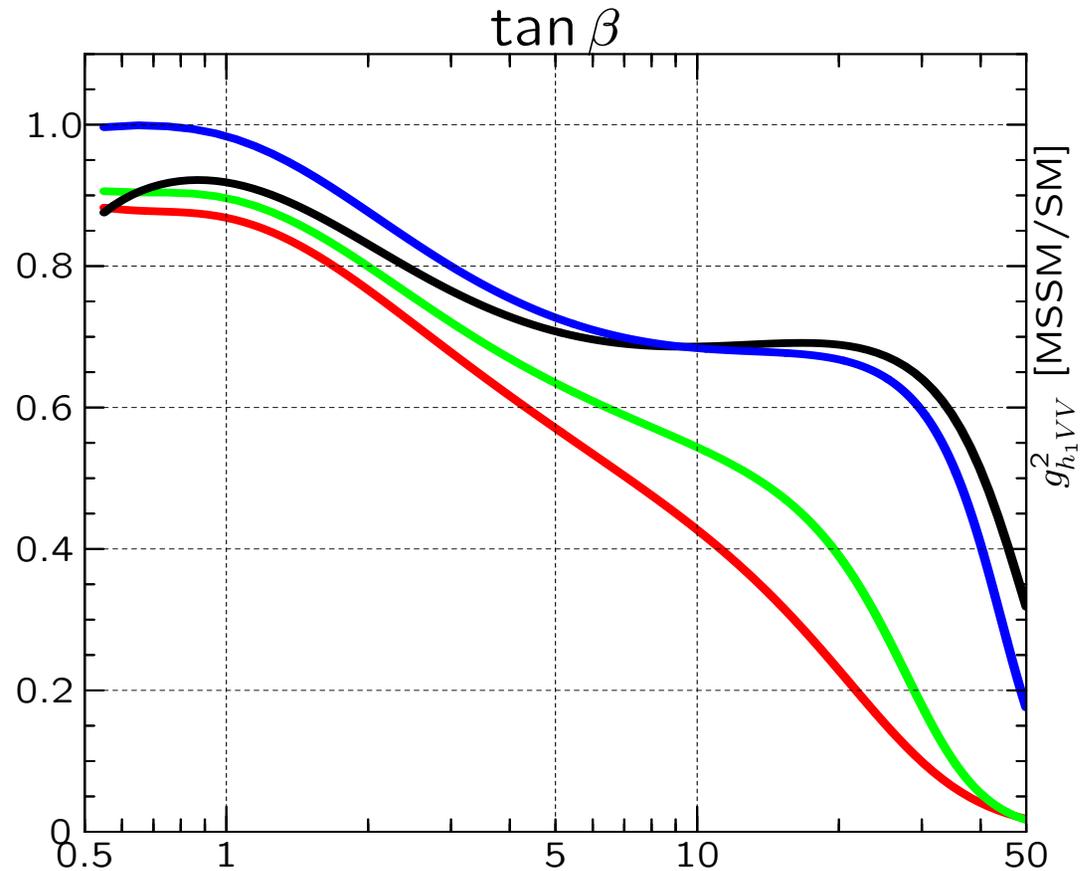


*FeynHiggs*,  $M_{H^\pm} = 150$  GeV ,      *CPsH*,  $M_{H^\pm} = 150$  GeV

*FeynHiggs*,  $M_{H^\pm} = 500$  GeV ,      *CPsH*,  $M_{H^\pm} = 500$  GeV

⇒ large differences, but understood

Compare  $h_1ZZ$  in the two scenarios for  $M_{H^\pm} = 150$  GeV :



*FeynHiggs*,  $m_h^{\max}$ , *CPsH*,  $m_h^{\max}$

*FeynHiggs*, gluophobic Higgs, *CPsH*, gluophobic Higgs

$\Rightarrow$  large differences, but understood

Some improvement in **Hdecay3.0** with *FeynHiggsFast* option:  
(default option: *subhpole* )

$m_h^{\max}$  benchmark scenario:

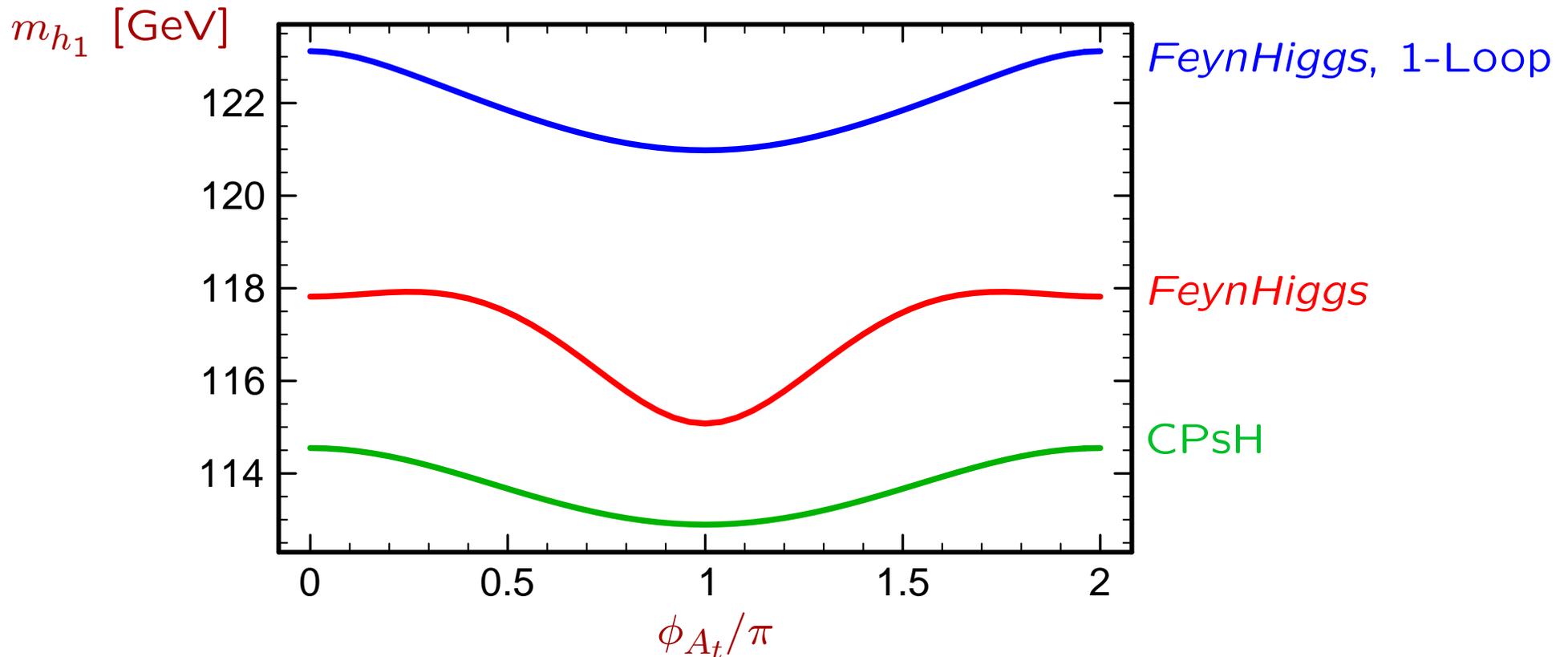
| $M_A$ (GeV), $\tan \beta$ | <i>HD3.0 (subhpole)</i> | <i>HD3.0 (FHF)</i> | <i>FeynHiggs</i> |
|---------------------------|-------------------------|--------------------|------------------|
| 250, 7.8                  | 125.1                   | 128.7              | 129.5            |
| 600, 6.9                  | 125.2                   | 130.0              | 129.7            |

⇒ but larger differences for other scenarios possible

## Comparison with CPsH for complex parameters:

One example with complex phases (taken from [S. Hesselbach et al. '03]):

$$m_{\tilde{t}_1} = 350 \text{ GeV}, m_{\tilde{t}_2} = 700 \text{ GeV}, m_{\tilde{b}_1} = 170 \text{ GeV}, |A_t| = |A_b| = 600 \text{ GeV}, \\ M_2 = |\mu| = 300 \text{ GeV}, \phi_\mu = \pi, \tan\beta = 30, M_{H^\pm} = 160 \text{ GeV}:$$



Differences of  $\mathcal{O}(3 \text{ GeV})$

Real case: more complete two-loop corrections in *FeynHiggs*

## 5. Conclusinos

- *FeynHiggs2.1* provides Higgs boson masses, mixing angles, couplings, branching ratios, etc.  
in the MSSM with/without complex parameters (and for NMFV)
- Beyond existing calculations:
  - full one-loop evaluation
  - $q^2$  dependence included

⇒ effects non-negligible: 1–5 GeV for subleading 1-loop,  
1–1.5 GeV for  $q^2$  dependent corrections
- Inclusion of complex phases at two-loop level beyond  $\Delta m_b$   
in preparation
- Possible:  
Stand alone vers. - call within Fortran/C++ - call within Mathematica
- Processing of Les Houches Accord data
- *FeynHiggs2.1* is available at [www.feynhiggs.de](http://www.feynhiggs.de)